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Databased simulation and reconstruction of the near shore geomorphological structure and sediment composition of the German tidal flats

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With an area of almost 10,000 km², the project area represents the tidal flats on Germany's North Sea coast. The tidal flats and their channels as well as morphologically highly active estuarine systems undergo significant erosional and sedimentational processes that prove difficult the assessment of sedimentological composition based on relatively few and temporally far stretched field measurements. The holistic databased simulation of both the internal structure of the soil itself and its sedimentary composition is based on around 21,000 measured surface sediment samples (from 1949 until recent) and yearly consistent digital bathymetric models, starting 1950, spatiotemporally interpolated in a 10 m grid resolution by the Functional Seabed Model. By utilizing the high temporal and spatial resolution of the bathymetric models, it is possible to quantify the seabed depth evolution (sedimentation and erosion) and to solve a differential equation to capture sedimentary evolution, a consistent and continuous three dimensional model of both the surface and the subsurface structures and sedimentary compositions can be generated. To further extend the volumetric extent of the model, around 16,000 sedimentary core samples are used to fill the spatial and consequently the temporal void between the lowest altitudinal range of validity of the aforementioned model segment to the lower boundary of the target model volume. This boundary is set to be the lower limit of the morphologically active or activatable space, which contains the volume of sediment that could be eroded in current climate conditions. The limit, generally speaking, can be expected to somewhat coincide with the base of Holocene sediments, as Pleistocene sediments – especially subglacial tills – generally take higher amounts of bottom shear stress to erode than unindurated Holocene sediments, which usually form tidal flat sediments. The purpose of the generated three dimensional model is to be able to derive sedimentological information in both custom spatial resolution as well as custom sedimentological classification as base and validation data for process based morphodynamic simulation models. With these enhanced models, the quality of the prognosis of morphological developments and stability of coastal areas as a tool for planning processes for coastal protection and maritime economy is expected to be increased.

EGU2020 – Sharing Geoscience online

Session GM6.3
Coastal morphodynamics: nearshore, beach and dunes

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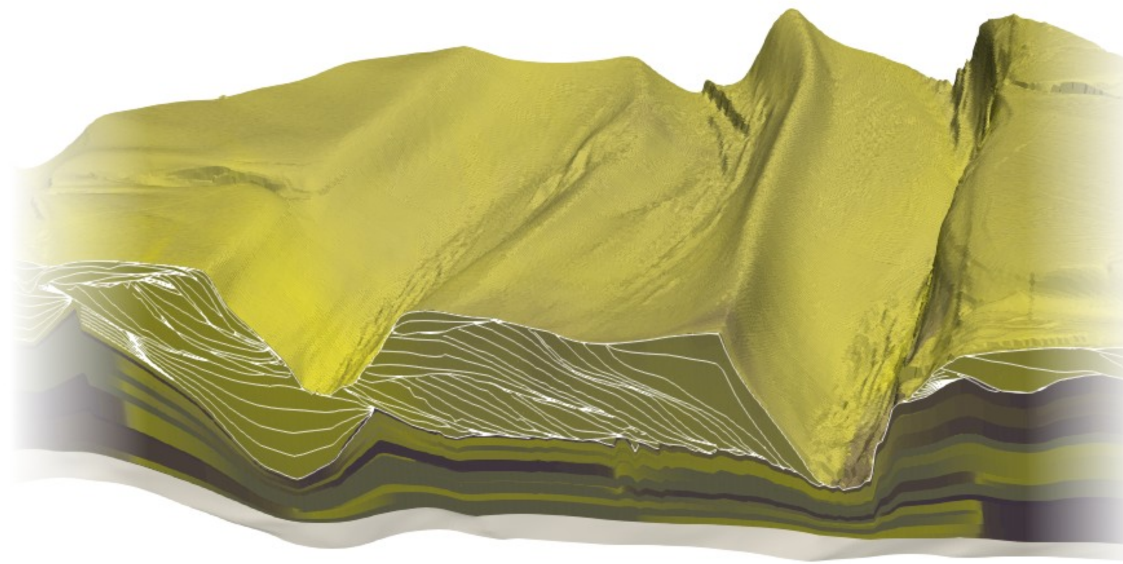

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2020-05-08

Introduction

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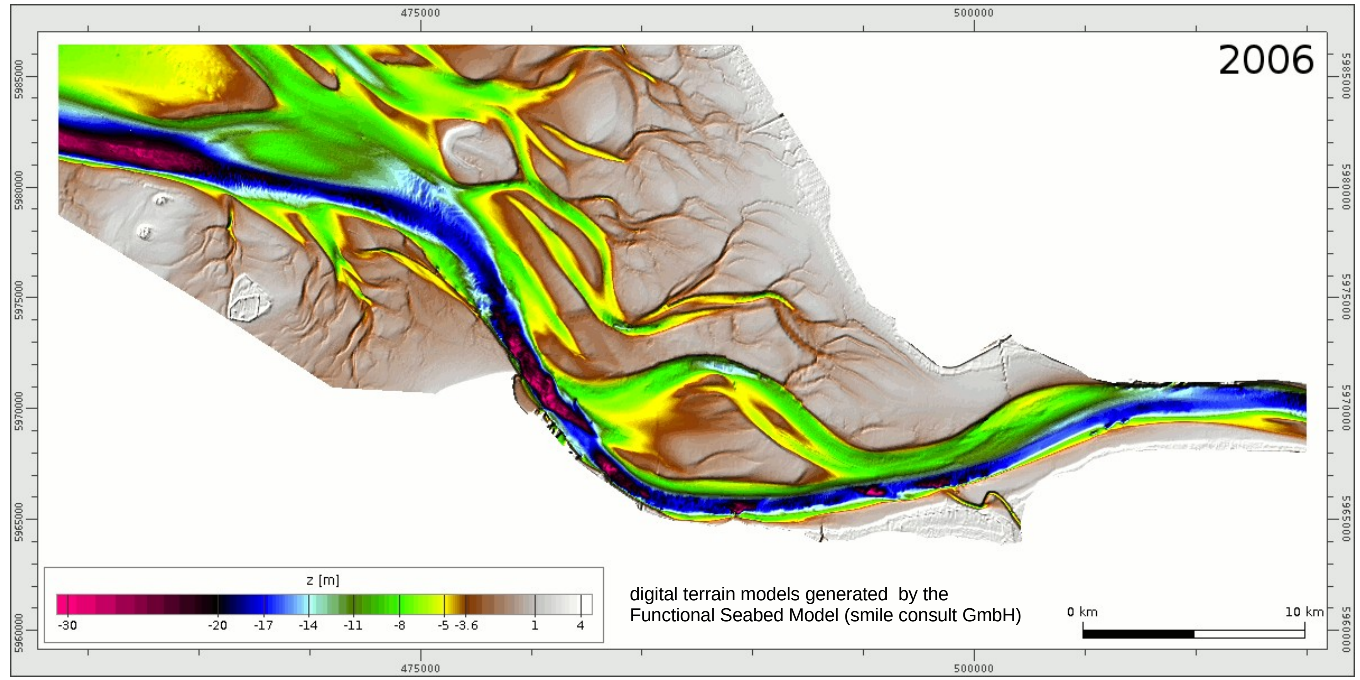

The German North Sea coast with its estuarine channels, barrier islands, and tidal flats is a morphologically highly active region. As is obvious in this segment of the Elbe estuary, substantial bathymetric and sedimentological changes can occur with a very high rate of as little as months or weeks.

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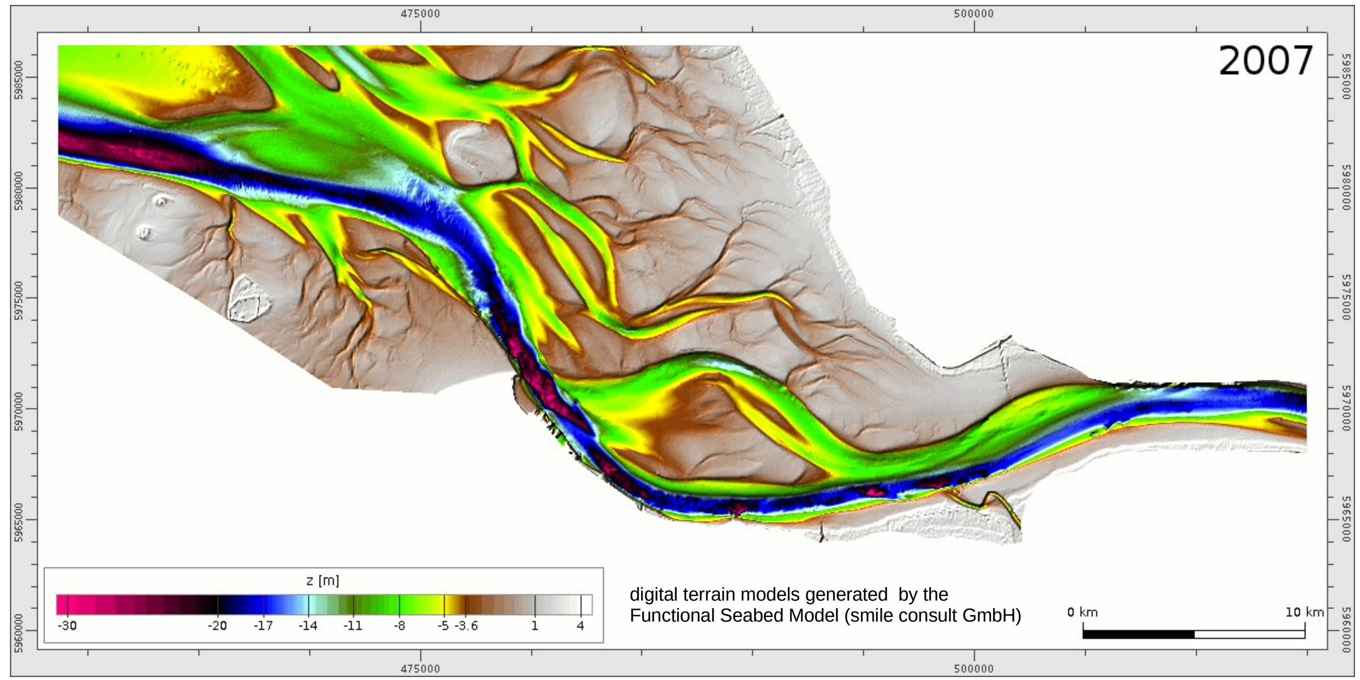

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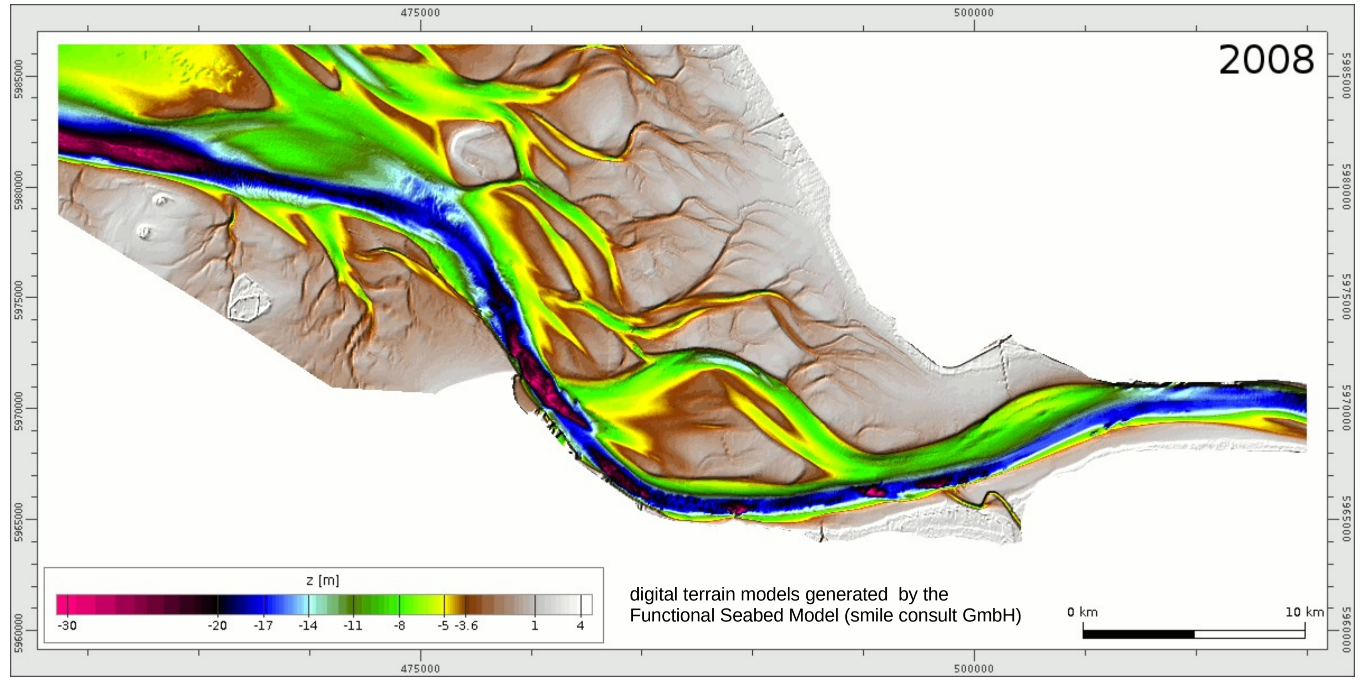

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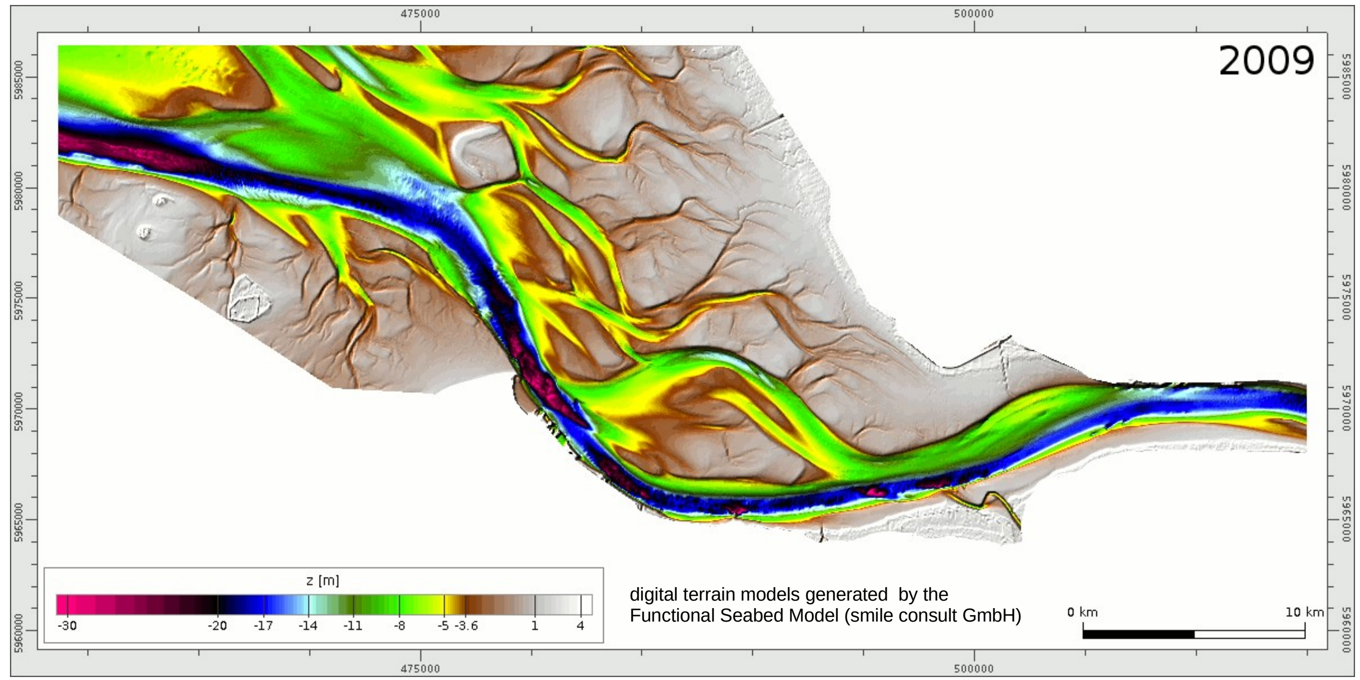

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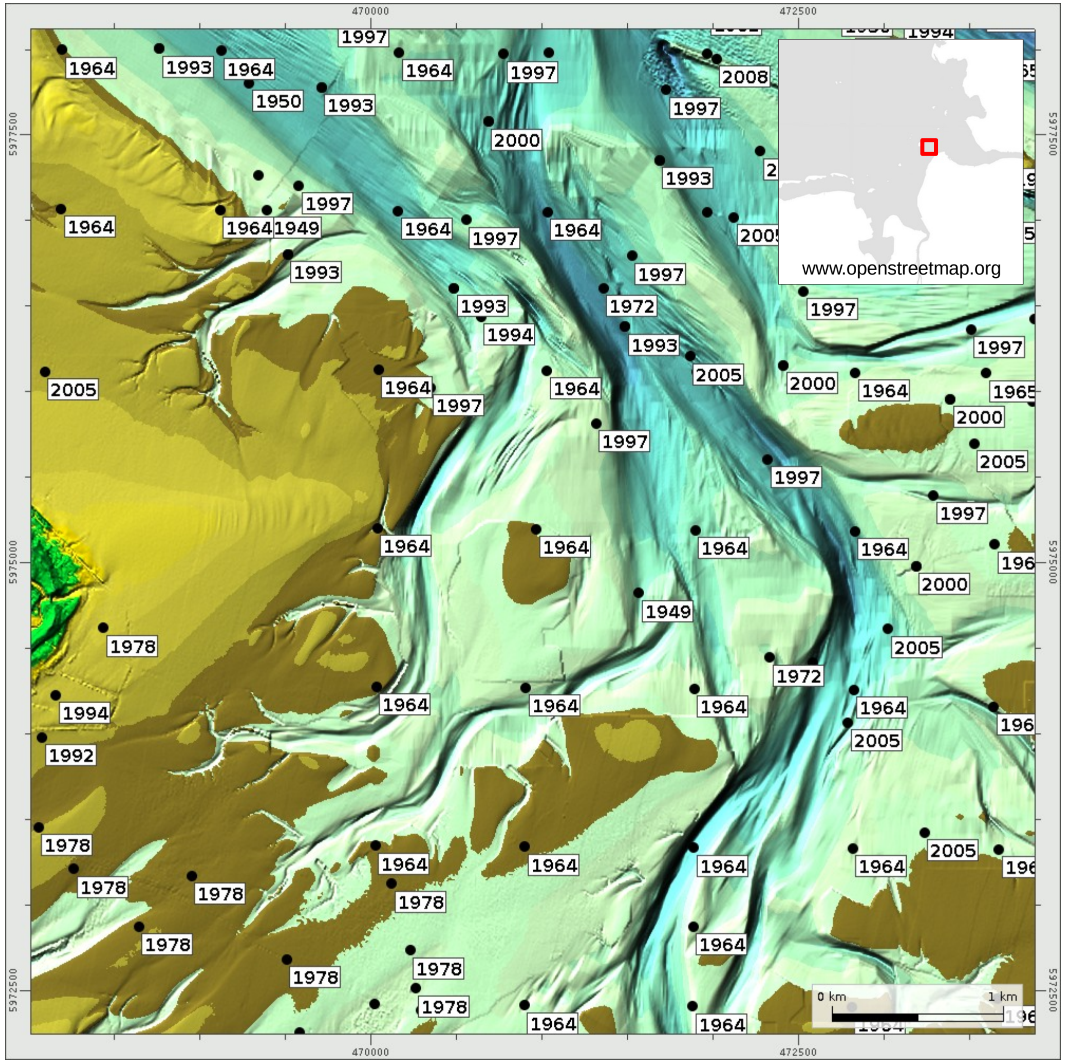


As is displayed in this segment of the Cuxhaven Tidal Flats, spatially reasonably dense sedimentological information might have decades of temporal gaps in between.

Considering the high rates of erosion and sedimentation in even a few years, let alone decades, sedimentological data sets need to be condensed into a holistic model using appropriate interpolation and approximation methods.

We present a databased **chrono-lithostratigraphical seabed model** that allows for a better understanding of longterm interconnected processes of hydrodynamics and meteorology and increases the quality of prognosis of coastal stability, which enables more accurate planning processes in coastal protection and maritime economy.

Introduction

To achieve a fully consistent and continuous 3D model, a three stepped procedure is applied:

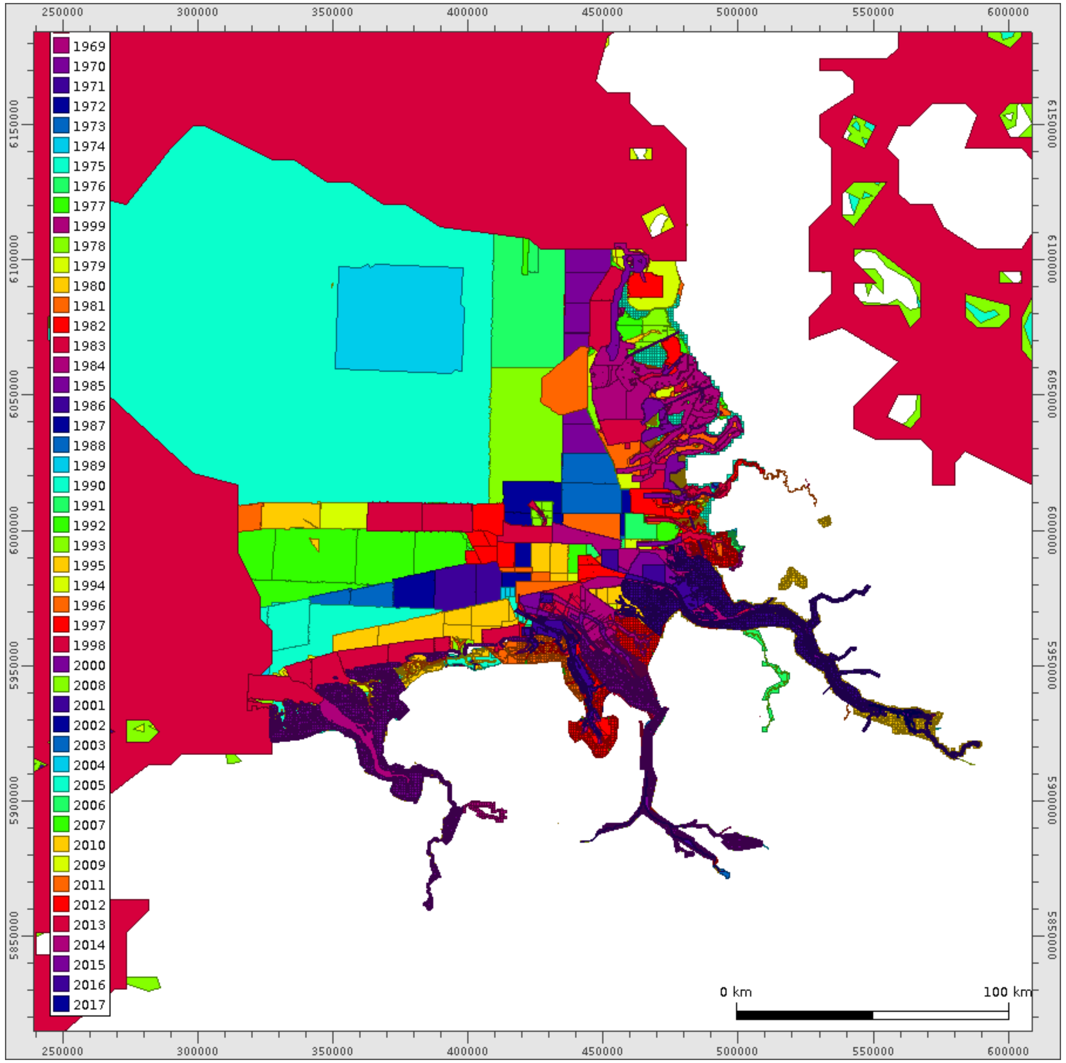
1) Data based simulation of geomorphological structures

2) Data based and process based interconnection of geomorphology and time dependent surface sedimentology

3) Data based integration of sediment core samples below the reach of the chronostratigraphical model component

Data based simulation of geomorphological structures

Data based simulation of geomorphological structures

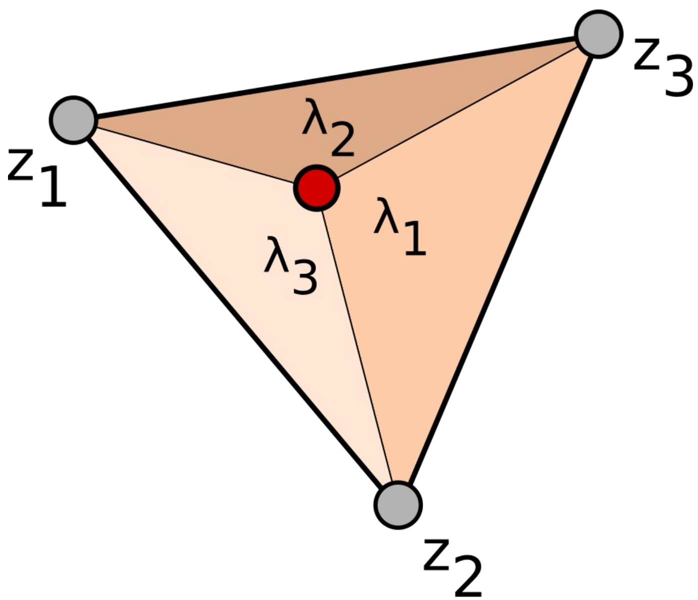


The simulation of the upper model parts geomorphology is based on the Functional Seabed Model (FSM), developed by smile consult GmbH (Milbradt et al., 2015).

The FSM is a data based hindcast simulation model with a prominent bathymetric component that uses ~110,000 datasets with ~92 billion point measurements, in places reaching back into the 1930s.

Due to the application of spatio-temporal interpolation approaches, a consistent temporal data base is required. As datasets before ~1950 are sparse, the data based simulation of the geomorpological structures is starting in 1950.

Spatial interpolation of point measurements



$$z_{int} = \sum (z_i * \lambda_i)$$

The first component of spatio-temporal interpolation is – as is obvious – spatial interpolation.

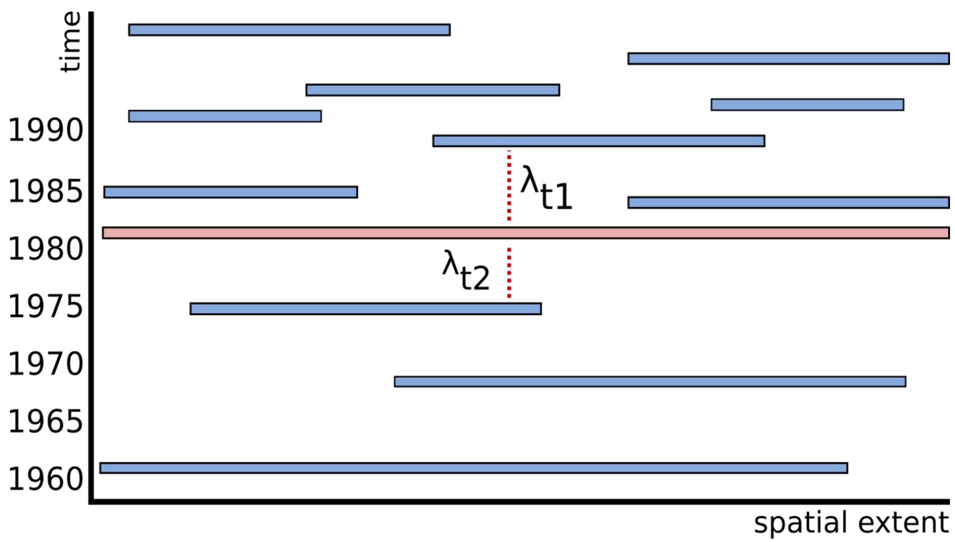
Spatial interpolation of single point measurements provides information on bathymetry between these single points.

The FSM utilizes various interpolation methods depending on the dataset, including structured grid based methods, unstructured element based methods (both triangular and quadrangular) and free point cloud methods.

For non recent bathymetric datasets, a triangulated irregular network (TIN) which uses linear interpolation (see figure) is most common.

Single point measurements thus become continuous spatial datasets.

Temporal interpolation of datasets



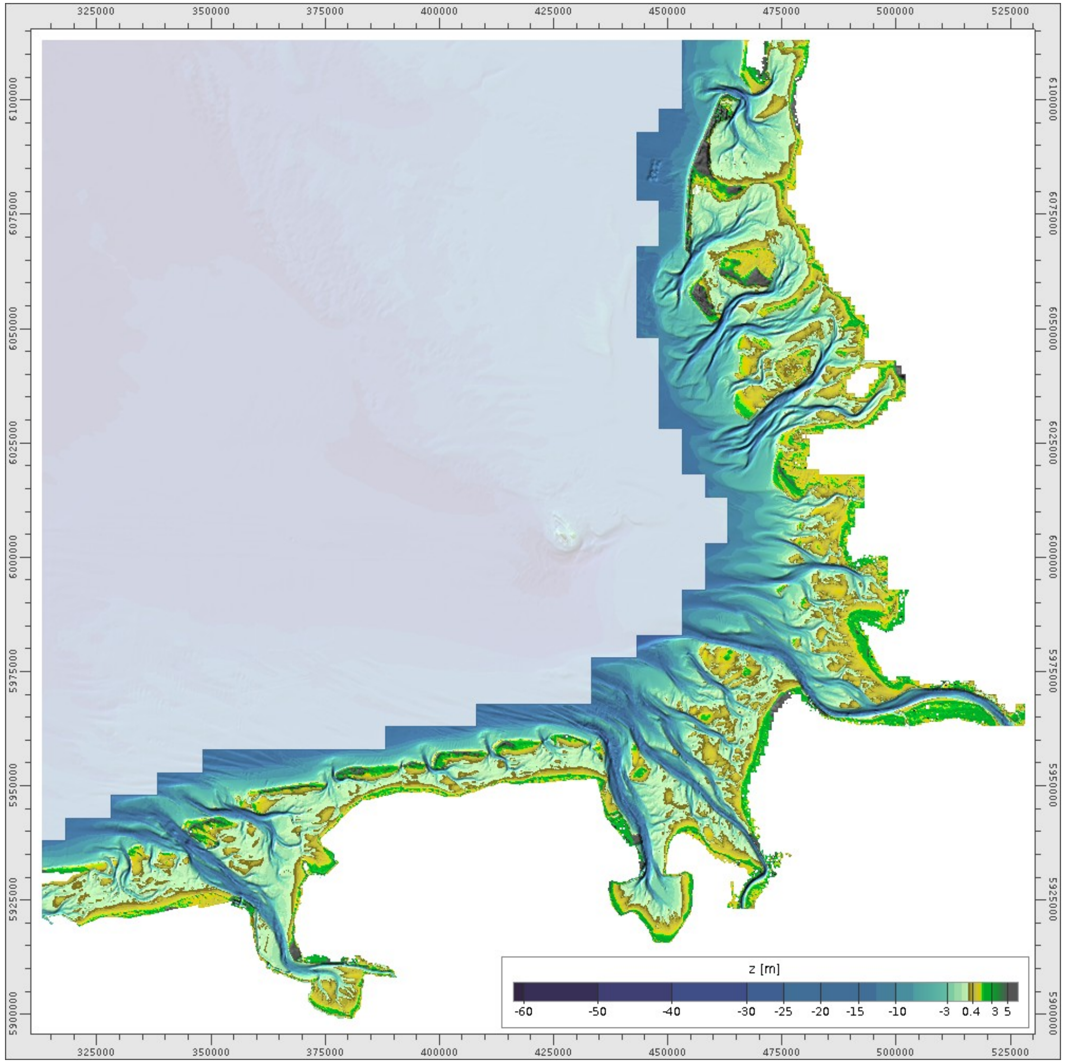
$$z_{int} = \lambda_{t1} * z_{t1} + \lambda_{t2} * z_{t2}$$

As datasets have a specific spatial extent, their temporal extent is usually even more limited. While each point measurement is only valid at the exact point in time when the signal was received, the combination of multiple points into a dataset produces a range of temporal validity, usually ranging between one day and several weeks.

To be able to reliably represent the geomorphological development, a linear temporal interpolation (see figure) can be applied to the datasets in the FSM: The closer the dataset is to the desired point in time, the higher the influence of its height value.

By combining spatial and temporal interpolation, a bathymetric height value can be derived at any point in time and space within the range of the FSM. The animation in the first slide is generated by application of this spatio-temporal interpolation approach.

Spatio-temporal interpolation to generate base DTMs



Digital terrain models (DTM) from the FSM span a certain area and are valid for a specific time.

In this context, an array of DTMs for the German North Sea coast is generated as of 1 July of each year from 1950 to 2016 with an area of ~10,000 km² each.

Each DTM is stored as 482 5x5 km gridded tiles with a grid resolution of x = y = 10 m.

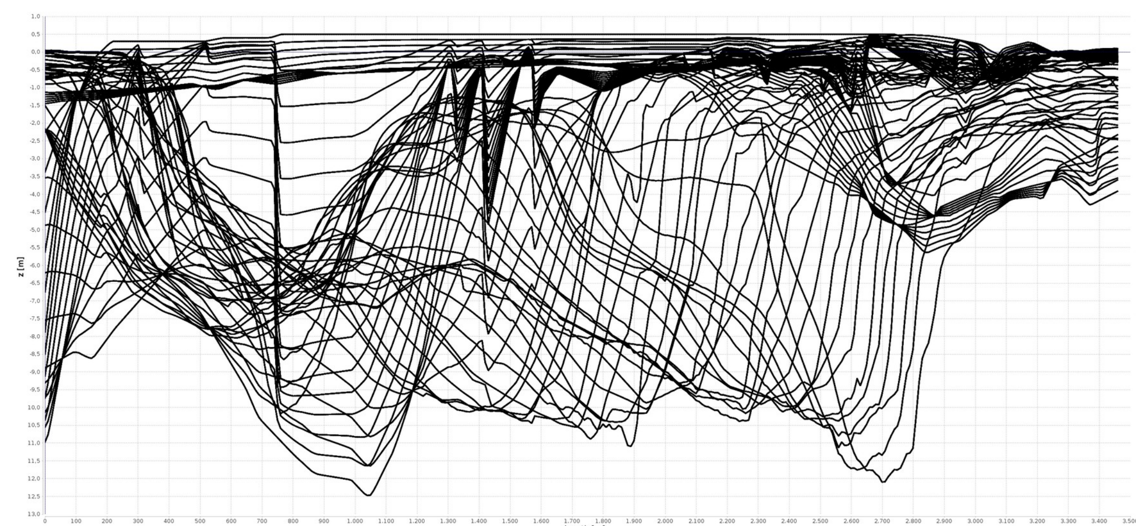
The figure displays the 2016 DTM tiles in a continuous colour model, with the background of the German Bight provided by the publicly funded project EasyGSH-DB.

A higher temporal resolution for the array was evaluated and subsequently rejected, as large scale structures already were detectable and smaller structures could not be resolved by a 10 m grid anyway.

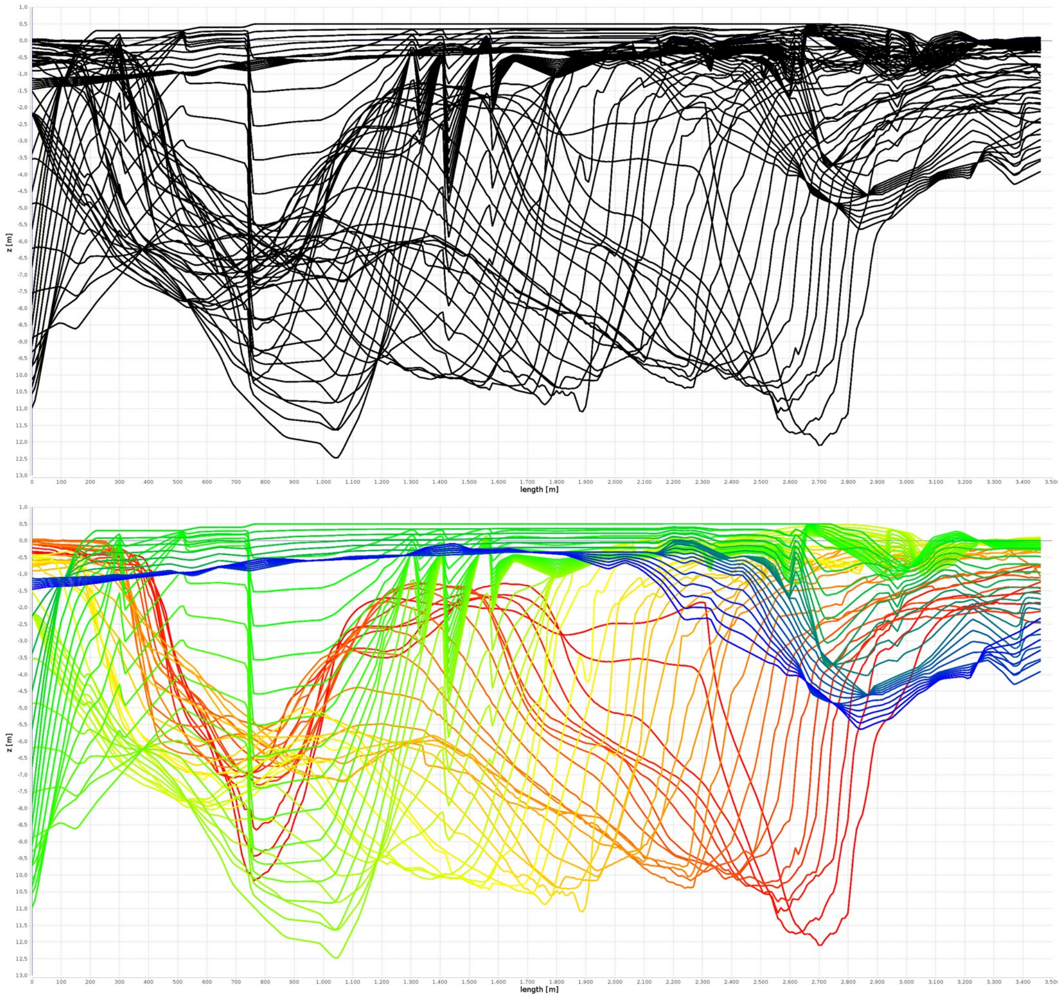
Data based simulation of geomorphological structures

Plotting all 67 DTMs in a single transect reveals the high complexity of the geomorphological evolution.

As is expected, sedimentation and erosion evolved the bathymetric surfaces to a significant amount.



Data based simulation of geomorphological structures



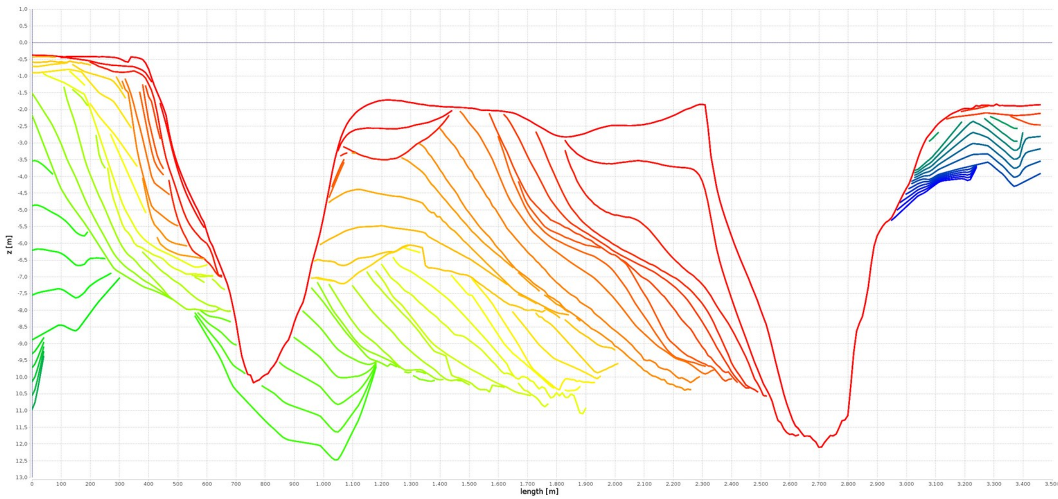
Assigning the temporal validity as a colour code – in this case blue represents old (1950s) and red represents young (late 2000s to 2010s) – it is conceivable that newer bathymetries in a significant amount of cases had to erode older bathymetries.

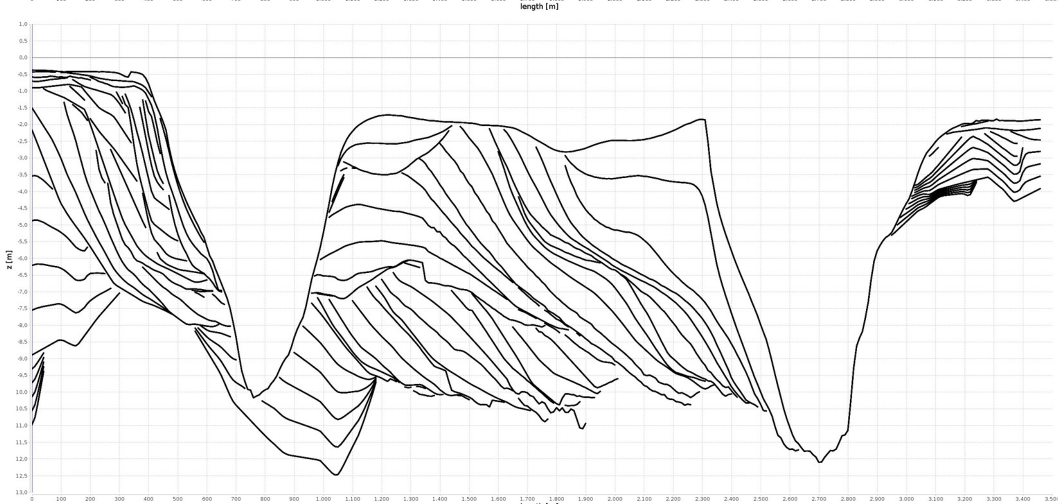
By analyzing each point of each DTM in relation to all younger DTMs, an erosional process had to be present, if one of the younger height values is lower than (or in this implementation equal to) the older height value.

After the analysis of all ~ 8.1 billion DTM points, any point that was classified as eroded was assigned an empty height value and effectively becomes a hole in the grid.

1950s 1960s 1970s 1980s 1990s 2000s 2010s

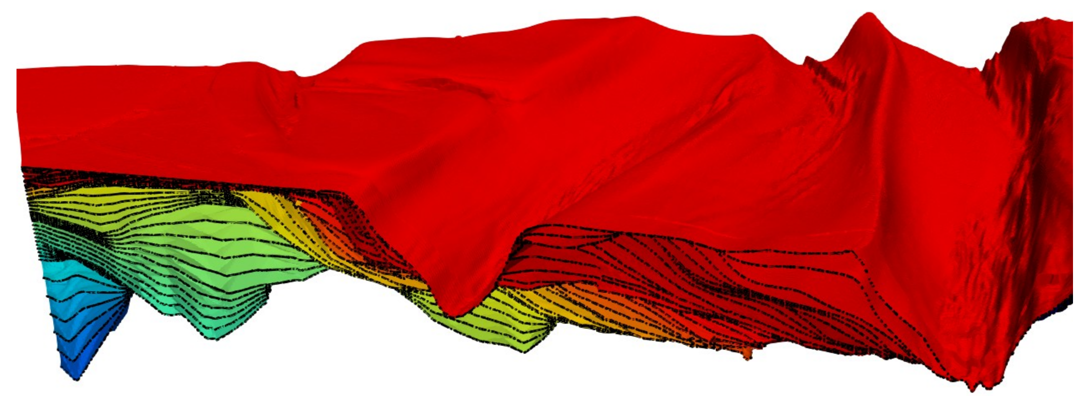
Data based simulation of geomorphological structures





The resulting processed DTMs represent the geomophological simulation of this model.

The figure below displays an extract of a layered 3D view of the geomorphological model part. The vertical scale and exact transect section differ, the colour model is equivalent.

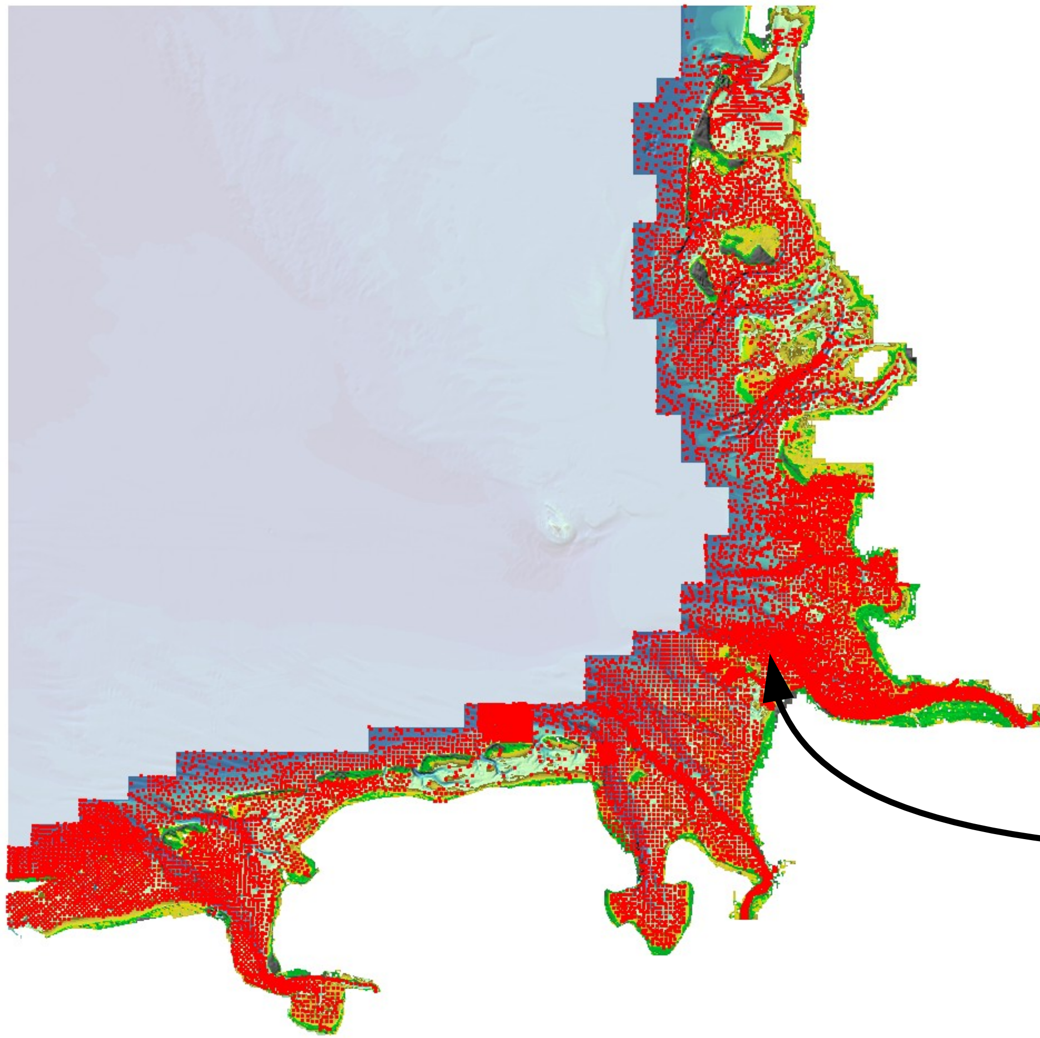


3D display with ParaView 5.6.0

1950s 1960s 1970s 1980s 1990s 2000s 2010s

Data based and process based interconnection of geomorphology and time dependent surface sedimentology

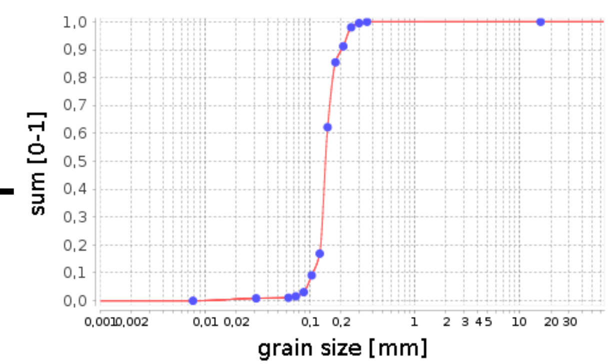
Interconnection of geomorphology and sedimentology



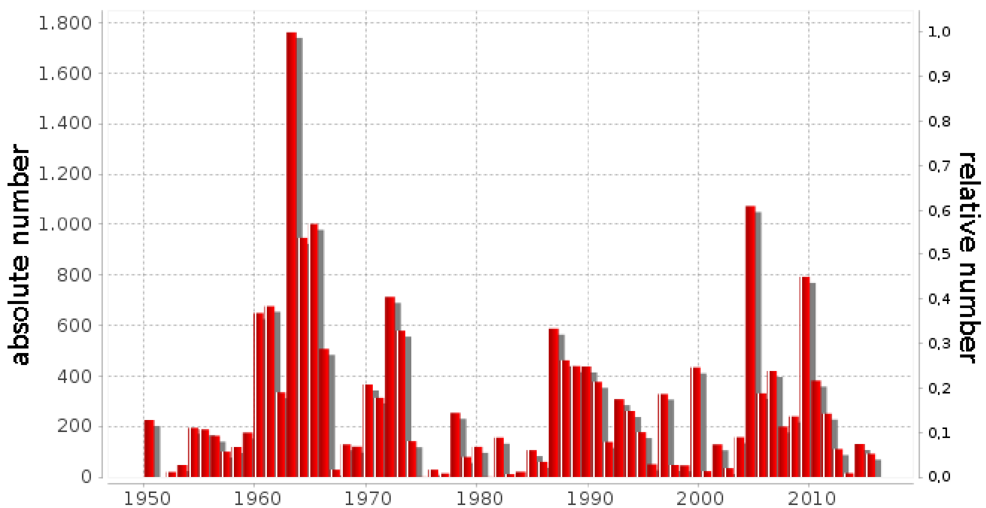
The most abundant sedimentological data type are surface sediment samples. Plotted in the figure aside is every surface sediment sample currently in use in generating the model.

As of now, 21,672 samples within the spatial model extent are converted into a usable format.

Each sample contains metadata such as owner, source and date, and most importantly the sediment distribution in form of a cumulative function.



Temporal distribution of samples



Out of these 21,672 samples 19,134 have a valid date attribute set (88.3% of total samples).

Out of these 19,134 samples 18,832 lie within the model range of 1950 – 2016 (86.9% of total samples).

A temporally uniformly distributed set of samples would provide around 281 samples per year, which is approximately one sample in 35.6 km².

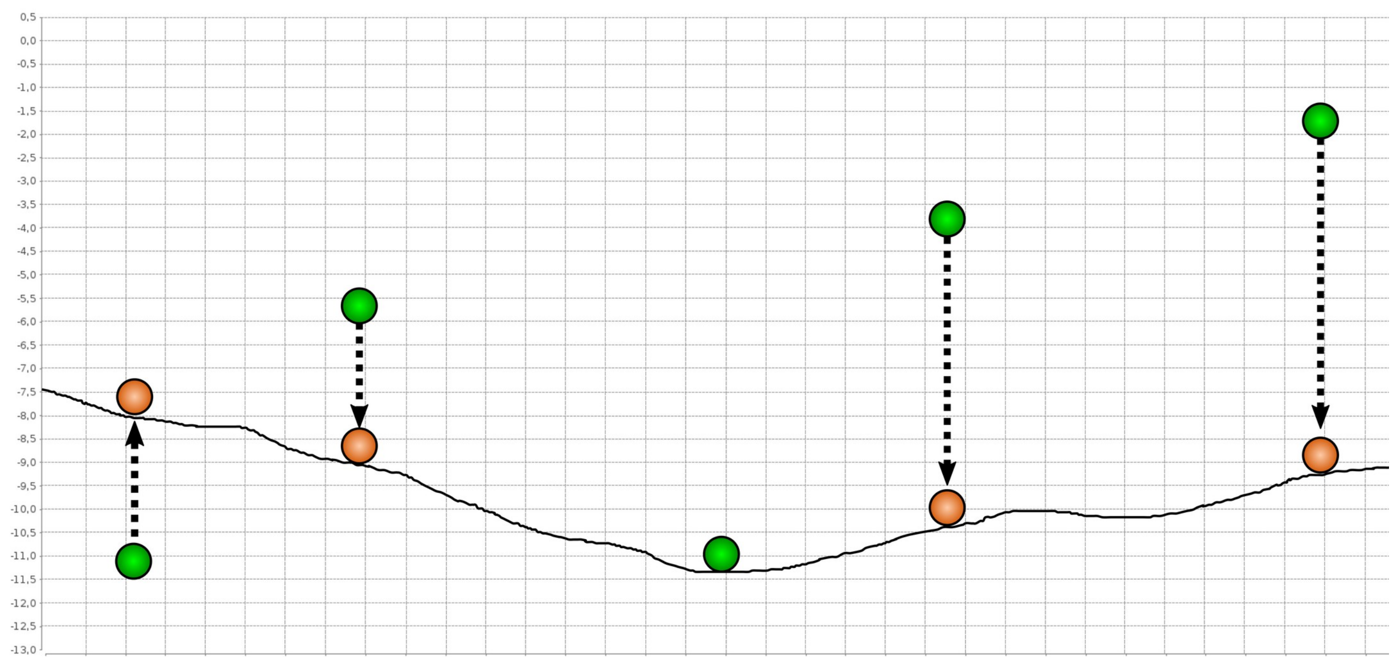
In reality, extensive measurement campaigns were concentrated to 1960s, early 1970s, around 1990s and since ~2004. This results in a range of samples per year to 0 – 1763.

Even in the most active year 1963, one sample on average was taken in every 5.7 km². Conceivably, in morphologically highly active regions with highly variable flow regimes, this is not nearly enough.

Model assumptions needed

A model assumption is needed to be able to extrapolate sediment samples from different years (and thus different bathymetric elevations) to the current year to be analysed. This way, even samples outside of the model range can be used, raising the number of samples per year back up to 19,134 or about one sample per 0.5 km² – each year.

This extrapolation is realized via parametrisation of the sediment distributions cumulative function in form of time dependent parameters d_{50} (median grain size), skewness and sorting.



Model assumptions

An adapted differential equation, as used in the processbased holistic morphodynamic model Marina (smile consult GmbH) is applied to calculate the time dependent parameters d_{50}, skewness and sorting.

Marina was and is successfully used for hydro- and morphodynamic analyses in inland water dynamics and for research projects in coastal areas.

$$\frac{\partial d_{50}(t)}{\partial t} = \lambda(t) \cdot d_{50}(t) \cdot (1 - n(t)) \cdot GF \cdot \frac{\partial z_b(t)}{\partial t} \cdot \sigma_0 \cdot \begin{cases} \left(1. - \frac{d_5}{d_{50}(t)}\right): & \textit{sedimentation} \quad \frac{\partial z_B(t)}{\partial t} > 0 \\ \left(1. - \frac{d_{50}(t)}{d_{95}}\right): & \textit{erosion} \quad \frac{\partial z_B(t)}{\partial t} \leqslant 0 \end{cases}$$

$\lambda(t)$ = *depth fuzziness factor: the lower elevation, the higher the eleveation uncertainty, the lower the dz influence*

GF = *gradient factor: the higher the gradient, the lower the influence of vertical dz changes*

$n(t)$ = *porosity: the lower the porosity, the denser the material, the harder the changes of* d_{50}

σ_0 = *initial sorting: the higher the value, the more potential for change of* d_{50}

d_5 / d_{95} = *lower / upper bound of possible* d_{50}*, determined by average distributions of surrounding samples*

Model assumptions

Based on the calculated d_{50}, the skewness and sorting parameters are derived as:

sorting:

$$so(t) = \sigma_0 \cdot \left(1 - \frac{d_{50}(t)}{d_{95}}\right) \cdot \left(1 - \frac{d_5}{d_{50}(t)}\right)$$

skewness:

$$sk(t) = \frac{(d_{95} + d_5) - 2 \cdot d_{50}(t)}{2 \cdot (d_{95} - d_5)}$$

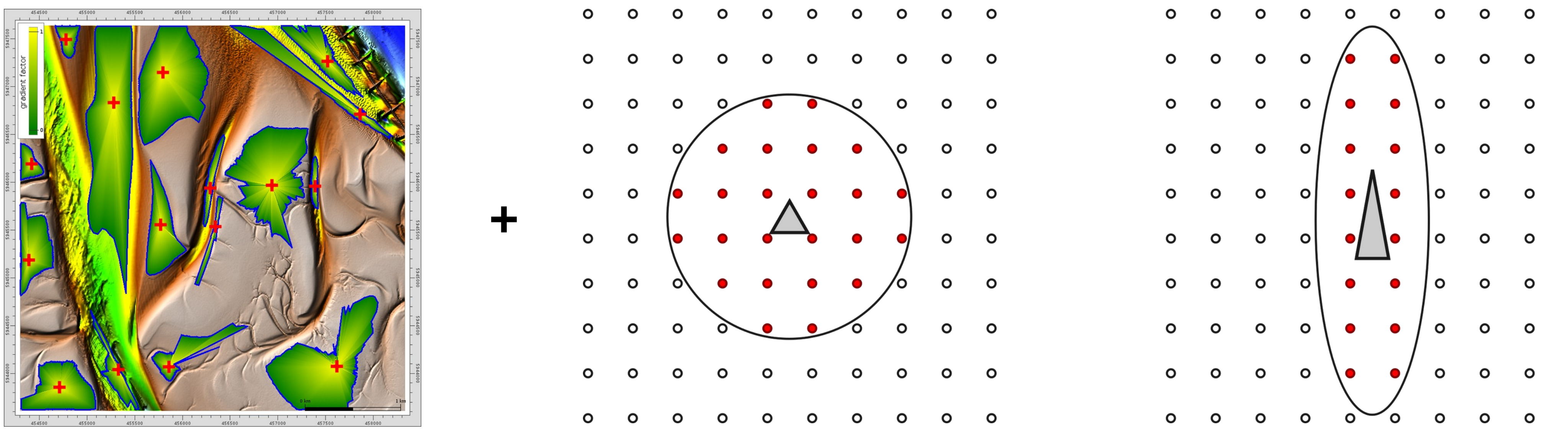
The resulting cumulative function can be calculated using these three parameters with grain sizes based on the Krumbein phi-scale (1934), as:

$$F(\phi) = \frac{1}{1 + \exp\left(\frac{1.7 \cdot (\phi - \phi_{50})}{(so - sk \cdot (\phi - \phi_{50}))}\right)}$$

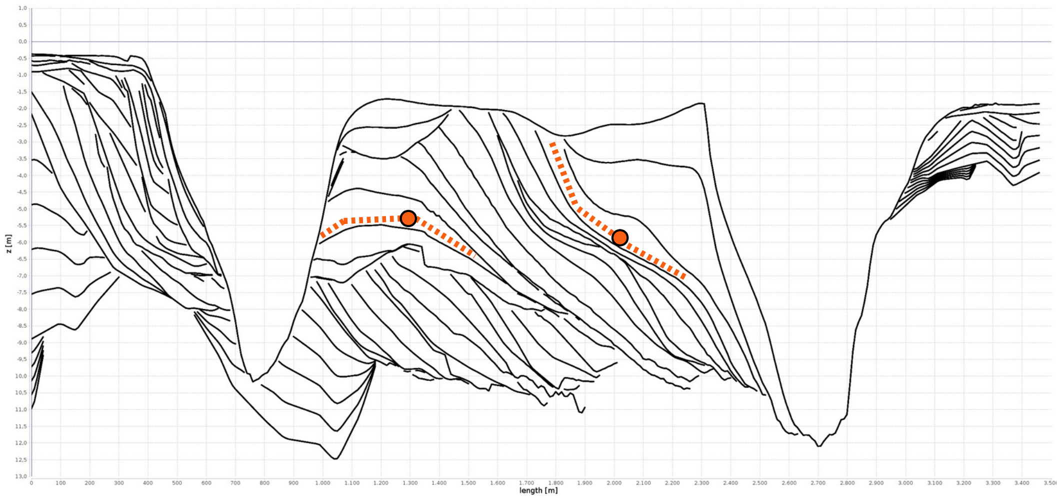
Spatial interpolation of sediment samples

The now temporally continuous function of grain size distributions is still locally isolated. To be able to add sedimentary information to the previously generated geomorphological model part, a spatial interpolation approach has to be applied.

An inverse distance approach, extended by anisotropic metrics based on bathymetric similarity and simulated resulting bottom shear stresses, is used for each year to interpolate a grainsize distribution for each point of each DTM tile.

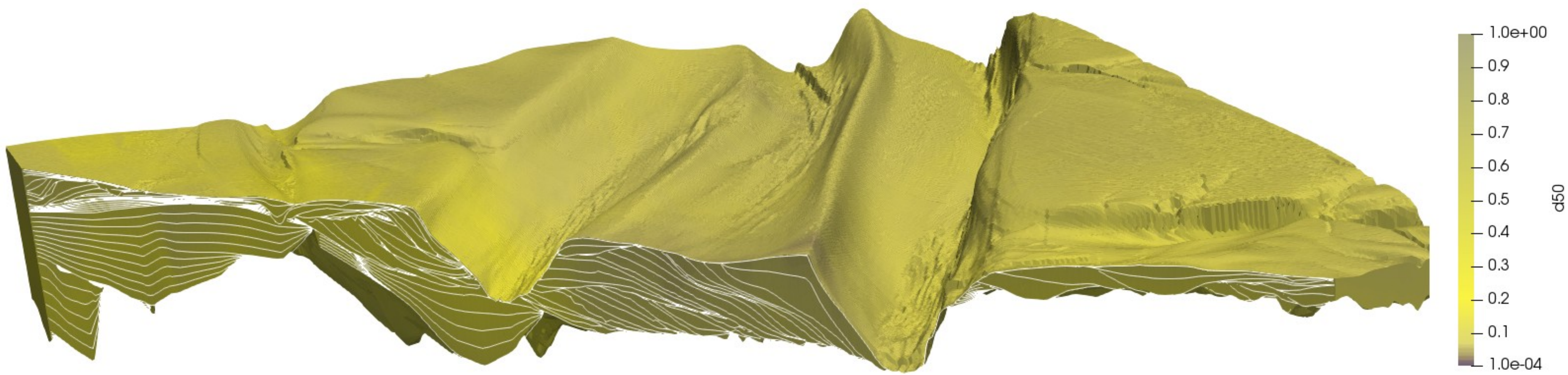


Chronostratigraphical model component



The resulting continuous three dimensional soil model will be called **chronostratigraphical component** in the following (see 3D illustration below).

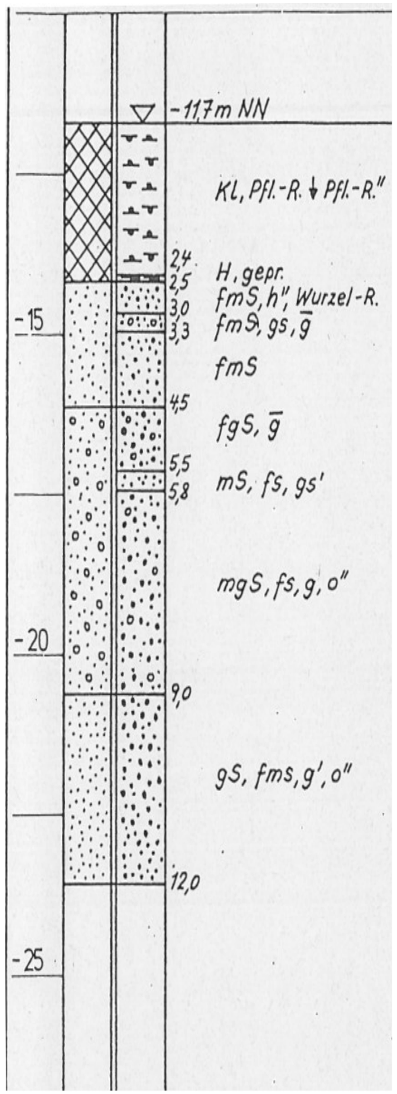
Even with the oldest bathymetry reasonably available, the desired vertical range of the model is not yet achieved.



3D display with ParaView 5.6.0

Data based integration of sediment core samples below the reach of the chronostratigraphical model component

Properties of sediment core samples



Sediment core samples are generally manually generated records, containing coordinates, total depth and information on the layer sequence, including layer thickness and linguistic description of the grain size distribution.

Although digital archives exist, the desired cumulative function as a distribution representative is very rarely stored.

Instead, the linguistic description can be parsed and transformed into a histogram of sediment classes and then be further processed into a cumulative function.

The processing of a German formatted linguistic description is possible used since 1982, when Voss devised a basic workflow.

Generation of lithostratigraphical model component

Beispiel einer Schichtbeschreibung im SEP-3 Format

Schichtbeschreibung: (fS, mS) (gs2, u1, fg (voe))

Bedeutung: Fein- und Mittelsand, schwach grobsandig, sehr schwach schluffig, vereinzelt feinkiesig

① Zerlegung des SEP-3 Formats

Hauptgemenge Nebengemenge

(fS, mS) (gs2, u1, fg (voe))

└ schichtbeschreibendes Adjektiv

└ Quantifikator

② Berechnung der Nebengemengeanteile nach VOSS (1982)

Grobsand (gs2) = 7.4 %
Schluff (u1) = 3.7 %
Feinkies (fg) = **11.1** %
└ **Fehler!** - schichtbeschreibendes Adjektiv nicht berücksichtigt

③ Verrechnung mit schichtbeschreibenden Adjektiven

Zugriff auf schichtbeschreibende Adjektive und Bewertungsliste (beschreibt das Verhältnis zu Quantifikator 3 - mittl. Gehalt)

„vereinzelt vorhanden“ (voe) = 10 % ⟶ vereinzelt feinkiesig (fg(voe)) = 1.11 %

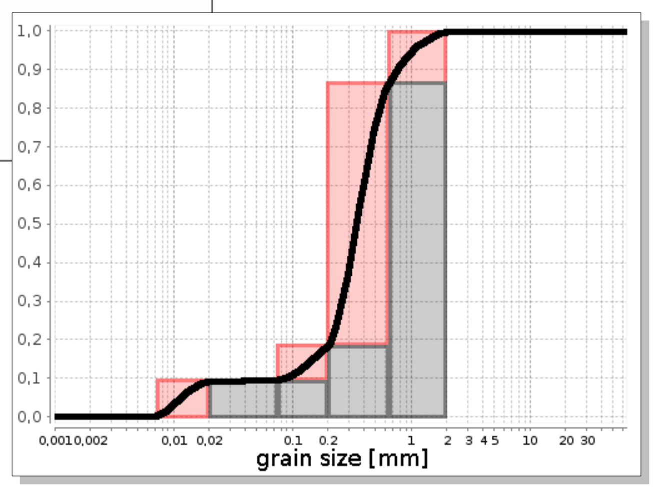
④ Berechnung der Hauptgemengeanteile nach VOSS (1982)

Feinsand (fS) = 43.9 %
Mittelsand (mS) = 43.9 %

Ergebnis der Berechnung

Feinsand = 43.9 %
Mittelsand = 43.9 %
schwach grobsandig = 7.4 %
sehr schwach schluffig = 3.7 %
vereinzelt feinkiesig = 1.1 %

Naumann et al., 2014

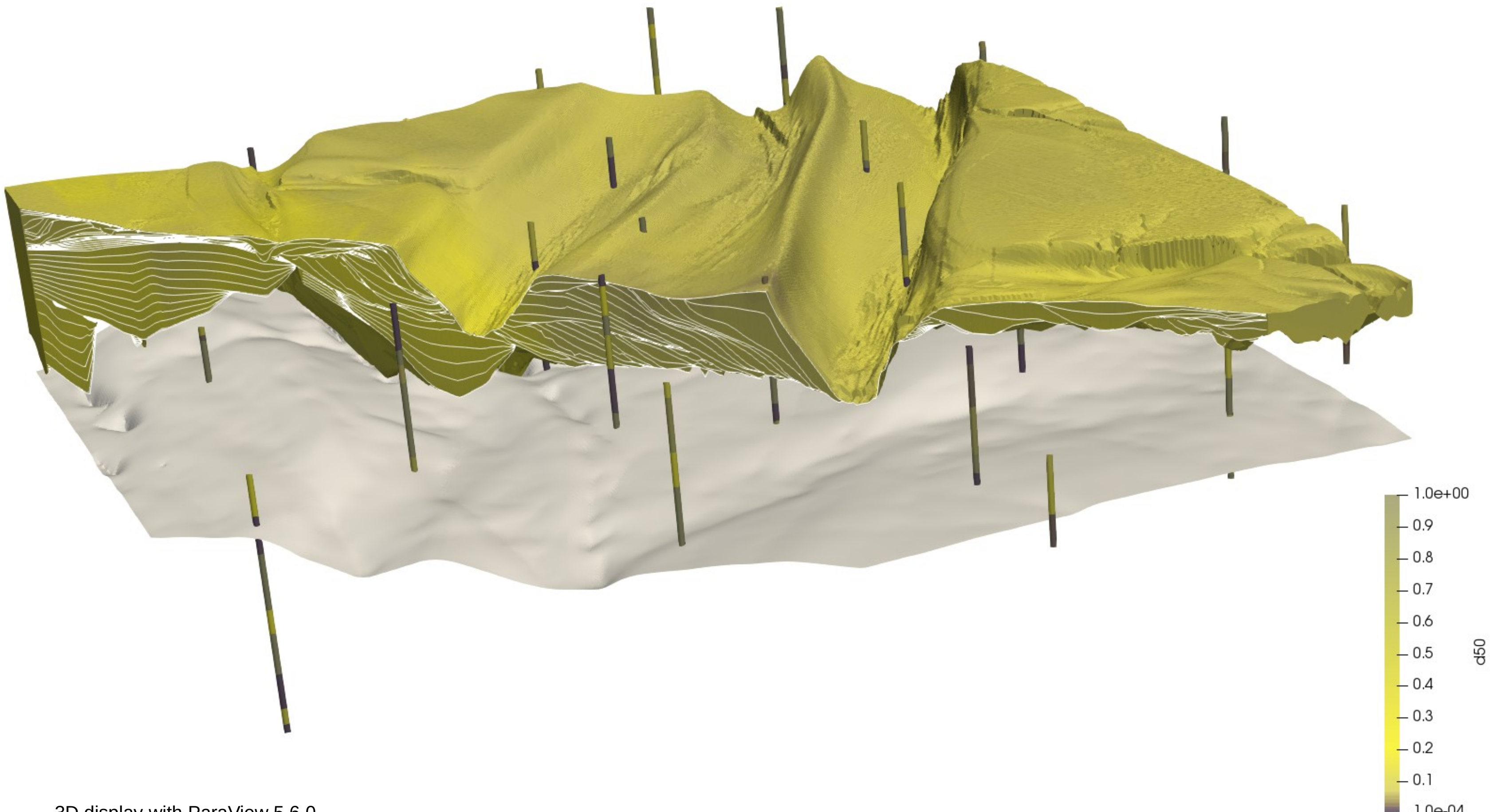


Naumann extended this processing by recognizing the impact of layer descriptive adjectives such as „sparsely“. These reduce the percentages to as low as 5% of the calculated value.

Adding up the grain size classes percentages enables the generation of a cumulative function, the foundation of the **lithostratigraphical model component.**

The reversal of this conversion with minimal loss is called (quasi-)bijective transformation (Sievers et al., 2019). It is highly useful for the generation of sedimentological maps and quality assessments of interpolation approaches that combine multiple cumulative functions, as used in the further generation of the lithostratigraphical model component.

Generation of lithostratigraphical model component



3D display with ParaView 5.6.0

Core samples, together with the lower boundary, i.e. an approximation of the holocene base, can be used to fill the vertical gap still present.

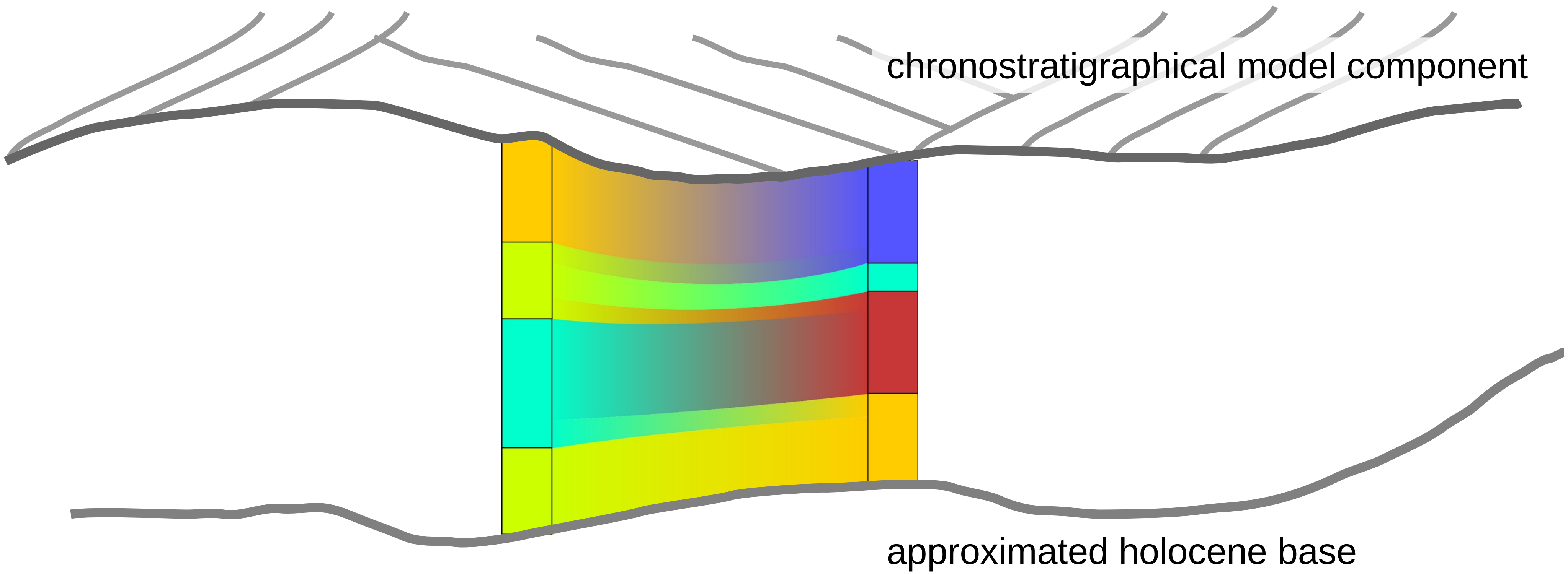
Note that core samples from the past might „stick out“ of the current model, because the core samples bathymetric depth might have been eroded.

Note that core samples vary greatly in quality and resolution. Due to this they are not considered in the chronostratigraphical component.

Generation of lithostratigraphical model component

As with the surface samples, the core samples too are laterally isolated, but an extended three dimensional interpolation is required.

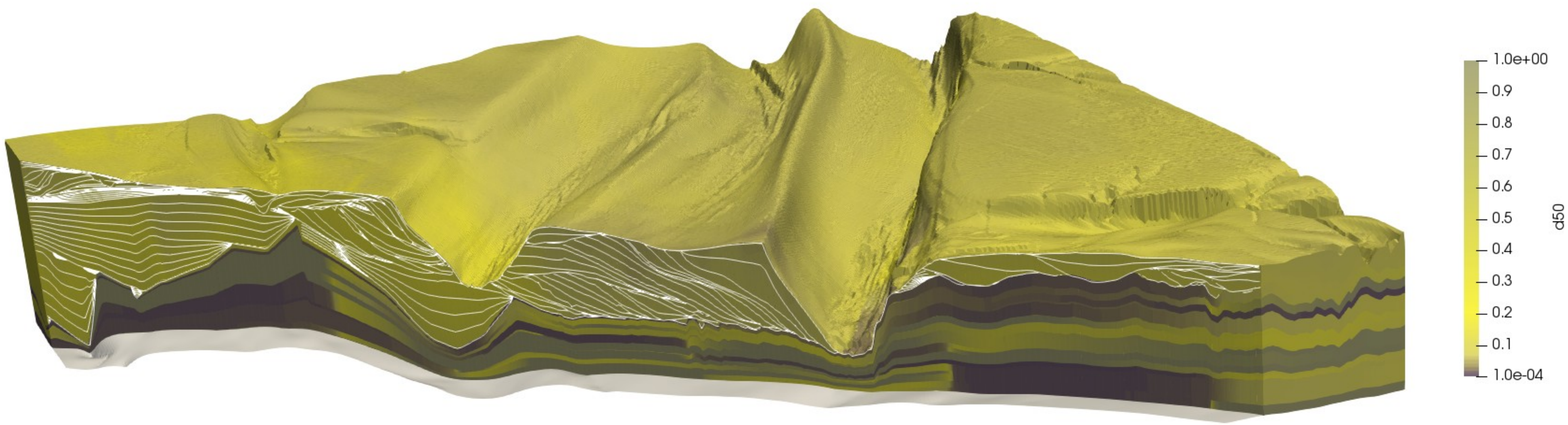
The interpolation approach between the core samples follows the curved bounding surfaces that are the lowest recorded bathymetry (that is the lower boundary of the chronostratigraphical component of the model) and the approximated holocene base, respectively.



The chrono-lithostratigraphical seabed model

This lower **lithostratigraphical model component** closes the void between the chronostratigraphical component and the lower model boundary.

Combining both components into the **chrono-lithostratigraphical seabed model** for the analyzed area of 10,000 km² allows for custom spatial and sedimentological extraction of information.



3D display with ParaView 5.6.0

Outlook

We see the greatest potential for further development in the improvement of the lithostratigraphical component. The orientation of the interpolation approaches for core samples is currently solely based on morphing of two bounding surfaces and could be extended by additional orienting surfaces extracted from seismic data.

Continuous updating of the chronostratigraphical components DTMs with more recent data while preserving older model versions results in a **time dependent** model of the soil structure and composition.

Cooperation with potential stakeholders:

- process based morphodynamic models with stratigraphical components (Delft3D, SediMorph..)
  - initial conditions
  - validation data
- biologists / ecologists (see Rubel et al., 2020)
- maritime economy (supply and disposal pipelines / cables)

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